

# A clue to the mechanism of $\Lambda K^+$ production in $pp$ -reactions\*

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## Abstract

We analyse the  $pp \rightarrow p\Lambda K^+$  total cross section data which were recently measured by the COSY-11 collaboration at an energy 2 MeV above the reaction threshold. Our analysis suggests that the measurement of the invariant mass spectrum for the  $\Lambda K^+$  at energies around 100 MeV above the threshold can provide a new constraint on the theoretical calculations for this reaction. In particular, the measurement can give a clue as to whether the reaction is dominated by resonance excitation or not. Thus, it should contribute to further understanding of the strangeness production mechanism. We show the invariant mass spectra for the  $\Lambda K^+$  system in these optimal kinematic conditions calculated by several approaches, and demonstrate that our suggestion is experimentally feasible.

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Recently the COSY-11 Collaboration [1] measured the total cross section for the reaction,  $pp \rightarrow p\Lambda K^+$ , at energy 2 MeV above the reaction threshold. The data were compared with the *theoretical models* which are presently available for this reaction [2, 3, 4, 5]. Among them, both the predictions of Sibirtsev [2] and Li and Ko [3] could reproduce the experimental data at this energy well only with the inclusion of pion and kaon exchanges, but without the inclusion of any resonances which are observed to decay to the  $\Lambda K^+$  channel. Moreover, it was found [2, 3] that the dominant contribution to the  $pp \rightarrow p\Lambda K^+$  reaction comes from the  $K$ -exchange mechanism. Alternatively, the study of Fäldt and Wilkin [5] which was made analogous to the  $pp \rightarrow pp\eta$  reaction with a nonrelativistic treatment including the final state interaction, suggests that the total cross sections for the  $pp \rightarrow p\Lambda K^+$  reactions at energies only slightly above threshold can possibly be explained by one pion-exchange followed by  $N^*(1650)$  resonance excitation. Furthermore, they claim that these two ingredients alone are almost enough to describe the data. One of their motivations was to study whether the same type of meson exchange model could be capable of explaining simultaneously the near-threshold  $\eta$  and  $K$  production data – one pion exchange followed by  $N^*(1650)$  resonance excitation for the present case.

In Ref. [4], within the resonance model, we performed the most detailed study of kaon production in proton-proton collisions with a full relativistic treatment. This included the mechanism adopted by Fäldt and Wilkin [5] as just one of the processes in evaluating the total cross sections. However, it has turned out that our calculation underestimates the data [1] at energy 2 MeV above the threshold – as shown in Fig. 1. It underestimates the experimental data from COSY by about a factor of 2, although it reproduces the existing data fairly well at energies more than 100 MeV above the threshold. One of the reasons for this underestimation is that our calculation [4] involves an incoherent sum of the contributions from each resonance, and thus would not usually be expected to reproduce the data well at energies very slightly above the threshold.

In Fig. 1 we also show the energy dependence of the total cross sections calculated using a *constant* matrix element, adequately normalized so as to fit the data (or adequately scaled phase space distributions multiplied by a constant factor) for the reaction – denoted by *phase space*. It implies that the experimental data at low energies can be described solely by phase space with a constant matrix element normalized to fit the data, because a similar energy dependence of the production cross section is also obtained by both the  $K$ -meson exchange model of Refs. [2, 3] and the resonance model [4], except for the absolute values. Thus, the total cross section data for this reaction at very low energies might not be sufficient to constrain the theoretical calculations even at energies slightly above the threshold – that is, to decide whether the reaction is dominated by kaon exchange without resonance excitation [2, 3], or by meson exchange followed by resonance excitation [4, 5]. Furthermore, it is difficult to decide what kind of meson exchange mechanism is dominant for the reaction as was questioned in Ref. [5].

In the lower part of Fig. 1, we show the separate contribution from  $\pi$ ,  $\eta$  and  $\rho$ -meson exchanges to the energy dependence of the total cross sections. In the calculation, we included the  $N^*(1650)$ ,  $N^*(1710)$  and  $N^*(1720)$  resonances. Their properties are sum-

marized in Table 1. Most of the coupling constants, cut-off parameters and form factors have been fixed by the previous studies for the  $\pi N \rightarrow YK$  ( $Y = \Sigma, \Lambda$ ) reactions [6, 8]. Together with the quantities newly appearing in the  $pp \rightarrow p\Lambda K^+$  reaction [4], we summarize the parameters of our model used for this study in Table 2.

Here, we should comment that the main features of our results are very similar to those of Fäldt and Wilkin [5]. In particular, the  $\pi$ -meson exchange is dominant at energies close to the reaction threshold. Moreover, the  $N^*(1650)$  resonance is strongly coupled to the pion, and thus gives the main contribution for the reaction, which can also be understood from Table 1. Furthermore, it should be emphasized that we are able to reproduce the data of COSY-11 [1] if we adopt the upper limits for the branching ratios for the  $N^*(1650) \rightarrow \pi N$  and  $N^*(1650) \rightarrow \Lambda K^+$  channels in Table 1. Indeed, the result was increased by a factor of about 1.8 when we adopted the upper limits in the calculation. Moreover, if we vary these branching ratios as free parameters, as was done by Fäldt and Wilkin [5], we will be certainly able to reproduce the experimental data from COSY [1].

However, such approaches cause two problems. First, with the same set of parameters, one should reproduce simultaneously the experimental data for the  $\pi N \rightarrow \Lambda K$  reaction. Indeed, the approach of the resonance model made previously [4] and again here uses the same parameter set consistently with that used for the study of the  $\pi N \rightarrow \Lambda K$  reactions as well as the  $\pi N \rightarrow \Sigma K$  reactions [6, 8]. Thus, our study for this reaction does not have much freedom to vary the parameters, nor to introduce new parameters. Second, the model should reproduce not only the recent data [1], but should also explain the data available at energies larger than 100 MeV above the threshold [9].

Keeping in mind the discussions made above, as well as the theoretical and experimental uncertainties for the  $N^*$  resonances, we may conclude that *in principle* both the resonance model and the model of Fäldt and Wilkin [5] can reproduce the data for the  $pp \rightarrow p\Lambda K^+$  at low energies, although this was not our motivation, nor the intention of the calculation [4].

Here, we point out further that a more definite conclusion can be drawn from the measurement of the  $\Lambda K^+$  invariant mass spectrum. This might also clarify whether the other resonances,  $N^*(1710)$  and  $N^*(1720)$ , may play a role in the reaction as well as the  $N^*(1650)$  resonance at relatively low energies near the threshold.

When the  $\Lambda K^+$  pair is produced through  $N^*$  resonance excitations, the invariant mass spectrum of the  $\Lambda K^+$  pair is expected to be influenced by the resonances<sup>1</sup>. In Fig. 2 we first show the spectrum of the  $\Lambda K^+$  invariant mass calculated with the resonance model at a excess energy,  $\epsilon = \sqrt{s} - \sqrt{s_0} = 10$  MeV, where  $\sqrt{s_0}$  is the reaction threshold, namely  $\sqrt{s_0} = m_N + m_\Lambda + m_K = 2.5503$  GeV with  $m_N$ ,  $m_\Lambda$  and  $m_K$  being the corresponding masses of the particles appearing in the final state. We show the spectrum calculated for the following three cases: 1) the total contribution from  $\pi$ ,  $\eta$  and  $\rho$ -meson exchanges with the inclusion of all the resonances,  $N^*(1650)$ ,  $N^*(1710)$  and  $N^*(1720)$ , 2) the separate contribution from pion exchange alone with the inclusion of all the  $N^*$  resonances, and 3) pion exchange with the  $N^*(1650)$  resonance alone. For comparison we also illustrate the phase space distributions with an arbitrary

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<sup>1</sup>Note that expected mass spectrum is not a simple Breit-Wigner distribution [10].

normalization. It is easily seen that the shapes of all spectra for the three cases at this energy are similar to that of simple phase space.

The reason is that the width of each  $N^*$  resonance is larger than the maximal total energy (when the proton in the final state has zero momentum) available for the  $\Lambda K^+$  pair,  $\epsilon = 10$  MeV. Because the upper limit of the spectrum is given by,  $\sqrt{s_0} + \epsilon - m_p = m_\Lambda + m_K + \epsilon$ , the range of the invariant mass distribution (i.e. the difference between the upper and lower limit for the spectrum) is equal to the excess energy,  $\epsilon$ , above threshold. Thus, for a small value of the excess energy,  $\epsilon$ , the structure of the corresponding resonance – in the present case the lowest baryonic resonance,  $N^*(1650)$  – cannot affect the shape of the  $\Lambda K^+$  invariant mass spectrum noticeably, because the width is much larger than the excess energy. Obviously when the quantity,  $m_\Lambda + m_K + \epsilon$ , is larger than the value,  $m_{N^*(1650)} + \Gamma_{N^*(1650)}/2$ , the mass spectrum will be certainly affected by this resonance – where,  $m_{N^*(1650)}$  and  $\Gamma_{N^*(1650)}$  are respectively the mass and width of the  $N^*(1650)$  resonance. Then, if resonance excitation is the dominant mechanism for the  $pp \rightarrow p\Lambda K^+$  reaction, we expect that the  $\Lambda K^+$  invariant mass spectrum will be certainly affected by the baryonic resonances under the condition,  $\epsilon \simeq m_{N^*(1650)} + \Gamma_{N^*(1650)}/2 - (m_\Lambda + m_K) \simeq 100$  MeV. (The  $N^*(1650)$  resonance will at first start to give a contribution as the energy increases.) In order to demonstrate that our argument is correct, we illustrate the  $\Lambda K^+$  invariant mass spectrum calculated at an excess energy of 100 MeV in Fig. 3, as an example. As can be seen from Fig. 3, the contributions of  $\pi$  and  $\eta$ -meson exchange become important when all the resonances,  $N^*(1650)$ ,  $N^*(1710)$  and  $N^*(1720)$  are included together. Furthermore, we emphasize that the result of the resonance model can be now distinguished from those of the simple phase space spectrum with an arbitrary normalization, and the pion exchange with the  $N^*(1650)$  resonance alone in our model. Thus, the measurement of the  $\Lambda K^+$  invariant mass spectrum may serve as a decisive test for the theoretical models and the mechanism for strangeness production.

It is of great interest that a measurement of associated strangeness production in proton-proton collisions is planned by the COSY-TOF Collaboration [11] in the near future. It is also crucial, to test our suggestion, that the experiment can be performed with a clear identification of the  $\Lambda$  and  $\Sigma$  hyperons in the invariant mass spectra – as was emphasized by Laget [12].

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Table 1: Summary of the resonance properties used in the present study. The confidence levels of the resonances are,  $N^*(1650)$ \*\*\*\*,  $N^*(1710)$ \*\*\* and  $N^*(1720)$ \*\*\*\* [13].

Resonance ( $J^P$ )	Width (MeV)	Decay channel	Branching ratio	Adopted value
$N^*(1650) (\frac{1}{2}^-)$	150	$N\pi$	0.60 – 0.80	0.700
		$N\eta$	0.03 – 0.10	0.065
		$\Lambda K$	0.03 – 0.11	0.070
$N^*(1710) (\frac{1}{2}^+)$	100	$N\pi$	0.10 – 0.20	0.150
		$N\eta$	0.20 – 0.40	0.300
		$N\rho$	0.05 – 0.25	0.150
		$\Lambda K$	0.05 – 0.25	0.150
		$\Sigma K$	0.02 – 0.10	0.060
$N^*(1720) (\frac{3}{2}^+)$	150	$N\pi$	0.10 – 0.20	0.150
		$N\eta$	0.02 – 0.06	0.040
		$N\rho$	0.70 – 0.85	0.775
		$\Lambda K$	0.03 – 0.10	0.065

Table 2: Coupling constants and cut-off parameters.  $\kappa = f_{\rho NN}/g_{\rho NN} = 6.1$  for the  $\rho NN$  tensor coupling is used.

vertex	$g^2/4\pi$	cut-off (MeV)
$\pi NN$	14.4	1050
$\pi NN(1650)$	$1.12 \times 10^{-1}$	800
$\pi NN(1710)$	$2.05 \times 10^{-1}$	800
$\pi NN(1720)$	$4.13 \times 10^{-3}$	800
$\eta NN$	5.00	2000
$\eta NN(1650)$	$3.37 \times 10^{-2}$	800
$\eta NN(1710)$	2.31	800
$\eta NN(1720)$	$1.03 \times 10^{-1}$	800
$\rho NN$	0.74	920
$\rho NN(1710)$	$3.61 \times 10^{+1}$	800
$\rho NN(1720)$	$1.43 \times 10^{+2}$	800
$K\Lambda N(1650)$	$5.10 \times 10^{-2}$	800
$K\Lambda N(1710)$	3.78	800
$K\Lambda N(1720)$	$3.12 \times 10^{-1}$	800

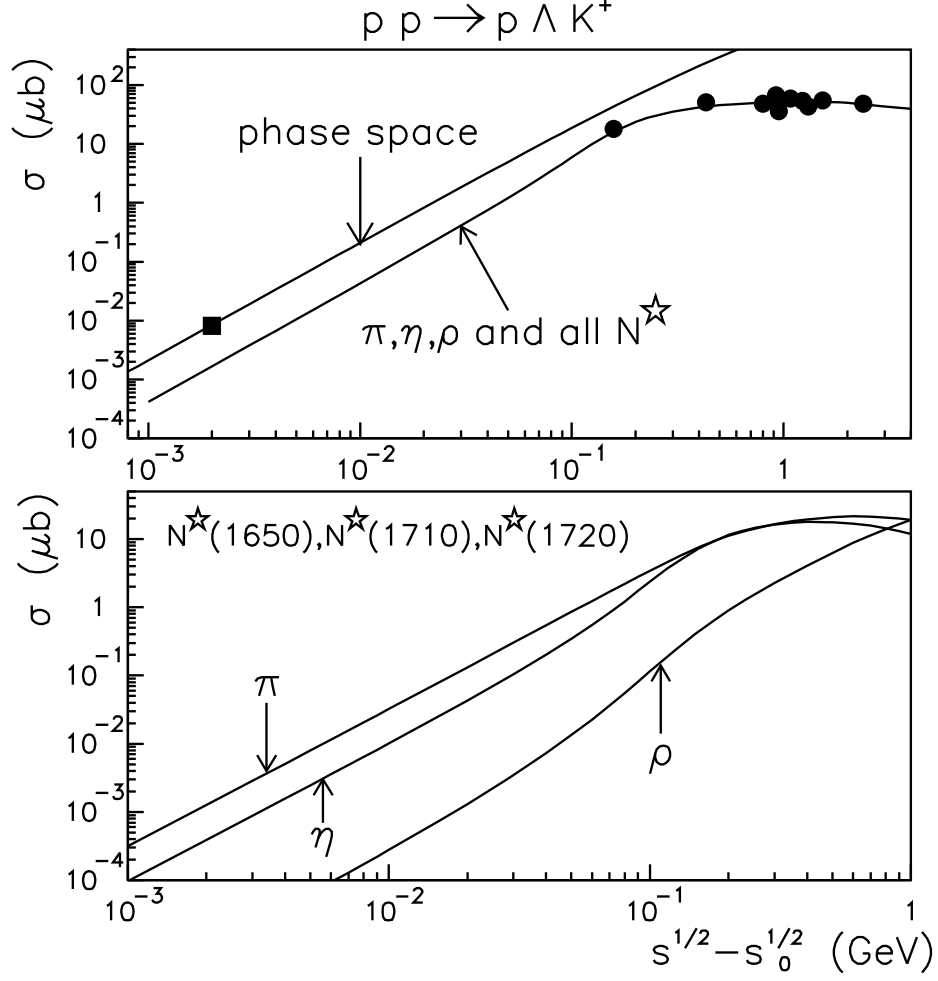


Figure 1: Energy dependence of the total cross section for the  $pp \rightarrow p\Lambda K^+$  reaction. The square indicates the experimental result of Ref. [1], while the circles are data from Ref. [9]. In the upper part of figure, the solid lines indicate the results of the resonance model, and the phase space considerations using the constant matrix element normalized so as to fit the data. The lower part in figure illustrates the separate contributions from  $\pi$ ,  $\rho$  and  $\eta$ -meson exchanges.

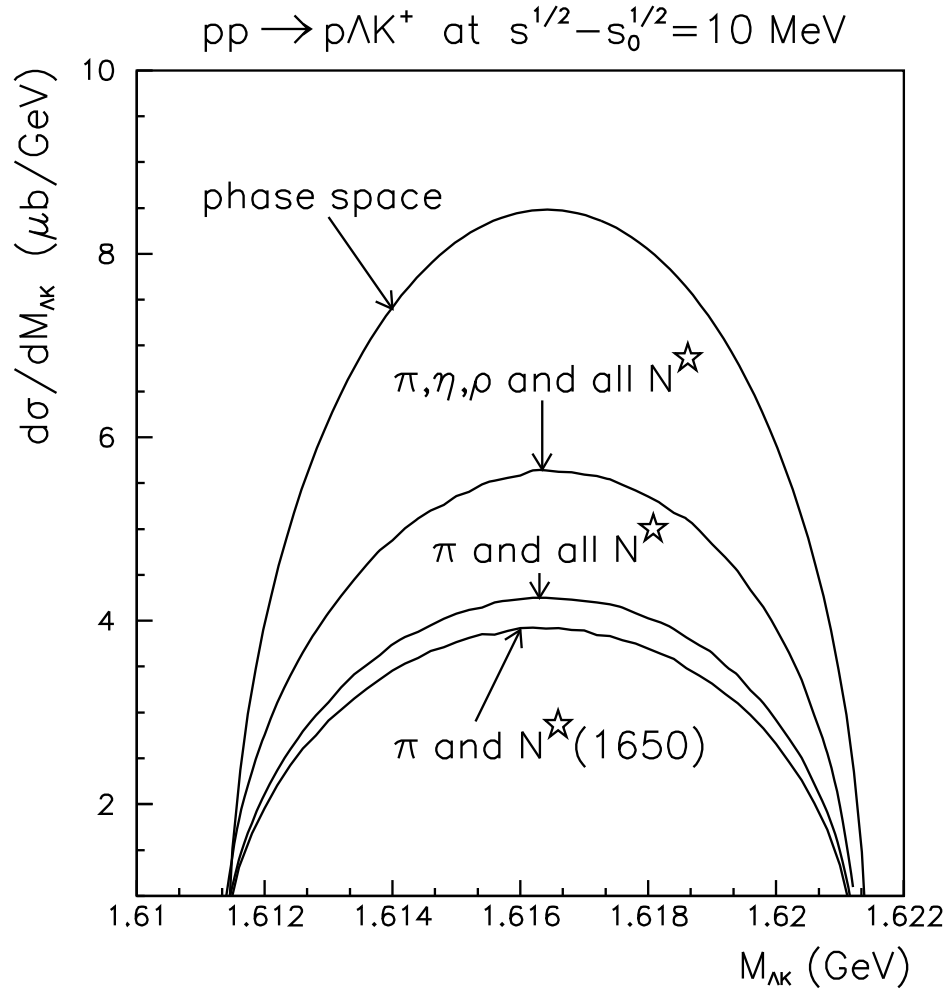


Figure 2: The  $\Lambda K^+$  invariant mass spectrum for the  $pp \rightarrow p\Lambda K^+$  reaction. Results are shown for the resonance model, and a simple phase space consideration with an arbitrary normalization. Here the reaction energy is 10 MeV above the threshold.



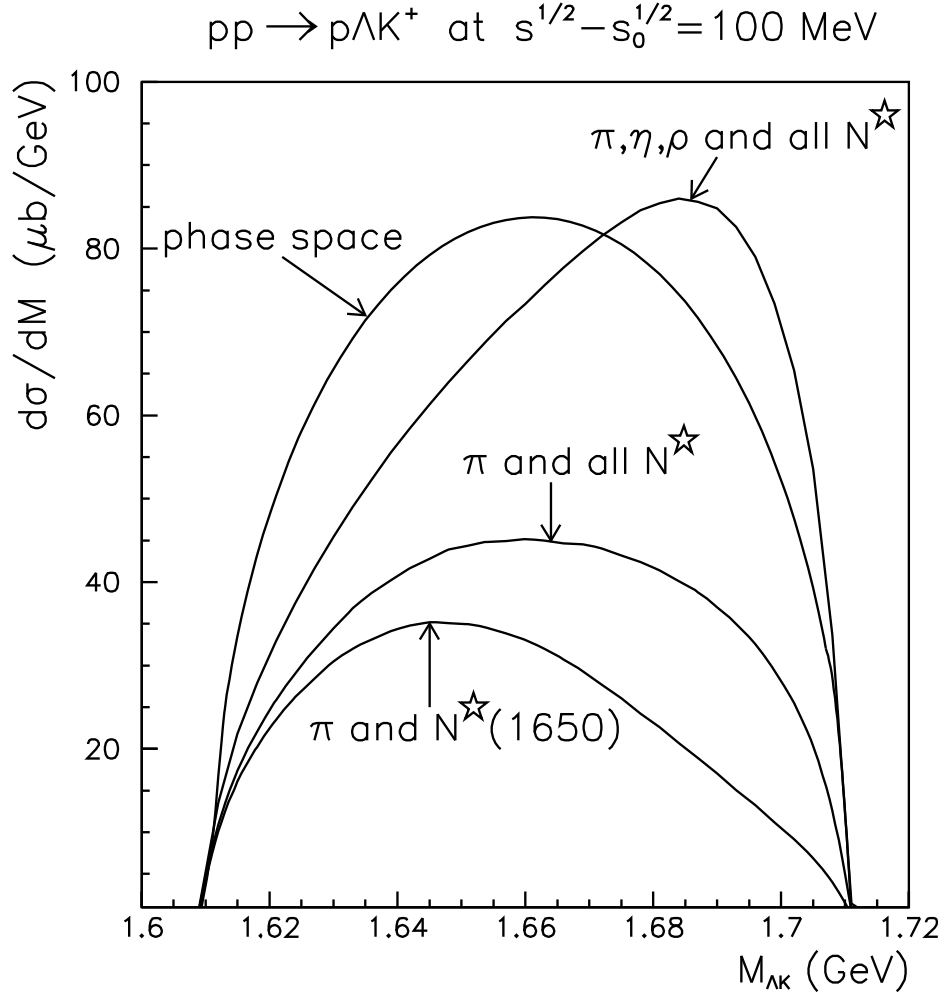


Figure 3: Same as Fig. 2, but the reaction energy is 100 MeV above the threshold.